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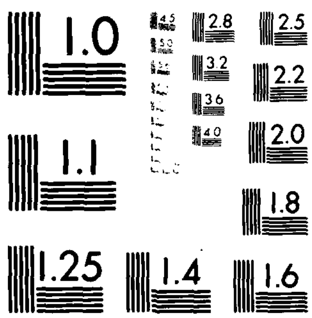

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DEFINITION OF THE PROBLEMS ASSOCIATED WITH AIR TRAFFIC CONTROL OF CLOSELY SPACED HELICOPTER TRAFFIC PERFORMING INSTRUMENT APPROACHES

R. W. SIMPSON

FLIGHT TRANSPORTATION LABORATORY
DEPARTMENT OF AERONAUTICS AND ASTRONAUTICS
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
CAMBRIDGE, MASSACHUSETTS 02139

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This study reviews the requirements for a modern, high performance all weather Air Traffic Management and Control System designed for U.S. Army airfields. A strawman ATM/C system is created to illustrate problems, and to identify research and development needs in surveillance, communications, and computer display and automation.

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SECTION 1

INTRODUCTION

This study reviews the requirements for a modern, high performance all weather terminal area Air Traffic Management and Control (ATM/C) System designed for US Army helicopter airfields. It assumes operations under Instrument Meteorological Conditions (IMC) and thus the availability of an microwave landing system at the landing pad and associated flight control system for the helicopters. It also assumes that the helicopters will be performing a Decelerating Steep Angle Approach and Landing (DSAL), either manually using a flight director, or automatically when coupled to the autopilot of the helicopter. Technological developments in recent years have demonstrated the feasibility of such approach and landing operations for an individual helicopter.

But this study reviews the traffic problems which arise when twenty or thirty such helicopters arrive in a short period at the landing site, with varying states of battle damage and fuel remaining. For the new all weather capabilities to be operationally useful, a modern, high performance air traffic control system must also be available so that a high rate of landings can be routinely achieved. A high landing rate requires very small distance separations on the DSAL. These small distance separations establish requirements for achieving precise spacings at the entry to DSAL, and close monitoring of actual separations on DSAL. Because of the possibility of a missed approach it also implies a tighter control over landing and takeoff operations at the heliport than is normally achieved under IMC conditions, thereby establishing requirements for high quality information displays and computer assisted decision making support for the human ATC controllers.

Thus, the air traffic problem establishes requirements for improved surveillance and tracking, improved air-ground communications, and improved controller displays. These are elements of the modern ATM/C system necessary to complement the landing system, and thereby achieve operational feasibility under IMC conditions.

SECTION 2

AIR TRAFFIC MANAGEMENT AND CONTROL SYSTEMS

There are four technological elements which contribute to the successful operation of an ATM/C system. On the ground, there are Surveillance and Tracking, Communications, and Computer Displays and Automation. In the air, there is the Navigation and Guidance Technology. To design and operate a successful terminal area ATM/C system, all of these technological elements must be developed and introduced in a compatible and evolutionary manner. The design task is not simple. It requires substantial effort in systems engineering and in simulation and analysis to ensure that the desired terminal area ATM/C system performance will be obtained from a given set of technological capabilities. It is unlikely that uncoordinate R&D efforts will produce a set of technological developments which constitute a successful ATM/C system.

The primary purpose of any ATM/C system is to provide "Separation Assurance" for all aircraft in the system. The system maintains separation from other aircraft, from terrain, from weather, and from enemy fire power. To accomplish this, the ATM/C system must gather information from a number of sources via ground communication with other ATM/C elements, via air-ground communication with the aircraft, and from surveillance equipment. It then controls the separation by controlling the flight path of aircraft usually by issuing flight path commands to aircraft and monitoring the conformance of aircraft to the planned path.

Since, in the usual case, the information on aircraft paths is gathered by a surveillance system with a low scan rate and varying position measurement uncertainty (which then requires a tracking algorithm to

determine speed and heading), there is a lag in obtaining information on aircraft paths. Also there is a further communications lag in the usual case where path commands are issued via radio broadcast by the ground controller to the pilot. Consequently, rather large separations are maintained by present civil and military ATM/C systems and only slow performance traffic flow rates can be achieved. If surveillance and communications performance can be improved, higher flow rates are achieved with equal levels of safety, or separation assurance.

An example of Separation Assurance, called the "Monitoring" function, occurs for helicopters on the DSAL where the longitudinal separation between successive helicopters gradually decreases as they approach the pad. The ATM/C system must monitor the actual separation to determine when safe separations are being violated, and must be able to issue a corrective command such as calling for one of the helicopters to execute a missed approach.

For terminal area ATM/C systems, there is another "Scheduling" function. A schedule of landings and takeoffs must be created dynamically for arrivals and departures at the site. This schedule determines an efficient sequence of landings and takeoffs such as to ensure safe separations, and it may also assign aircraft to multiple approach paths and pads when they exist. Given the schedule, flight paths for the arriving aircraft must then be determined such as to ensure correct spacing at entry to the final approach. This is another function called "Path Generation".

As the traffic flow rate increases, this "Scheduling" function becomes complex and rapidly changing until it finally requires computer aided decision support for the human controller. A simple version of "Scheduling"

called "Metering" is discussed in this report. It controls the rate of arrivals into the terminal area such as to prevent peaking of the number of aircraft arriving for final approach.

Another function of terminal area ATM/C systems is "Spacing". At the entry to the final approach, helicopters are "vectored" in heading and speed to achieve a desired position behind the preceding helicopter on approach. If precise spacings are to be achieved, the looseness of the flight path command loop must be overcome. Thus, precision surveillance, and good tracking algorithms (perhaps aided by knowledge of the current flight path commands) are required and the communications lag (both in issuing a command and getting a timely response from the aircraft) may need to be overcome by using a digital data link to display the command to the pilot; or, if the aircraft is within coverage of a microwave landing system, the data link may establish the track to be followed by the aircraft to achieve precise spacing.

The performance demanded of the ATM/C system in:

1) Monitoring separation assurance on approach;

2) Precise spacing in delivery to approach;

3) Efficient scheduling of landings and takeoffs;

will determine the capabilities required in terms of surveillance and tracking, in air-ground communication speed, and in improved controller displays and computer decision support. The basic parameter which establishes performance of a terminal area ATM/C system is the desired landing rate.

SECTION 3

DESCRIPTION OF TERMINAL AREA ATM/C OPERATIONS

3a. The Operational Scenario

The operational scenario which is foreseen for a terminal area ATM/C system for US Army helicopters is described in this section. A landing site is located somewhere in the rear of the combat zone. Low flying helicopters are randomly arriving for resupply, refuelling, and rearming, some with emergency conditions due to low fuel or battle damage. Tactical helicopters are departing with some urgency in fulfilling mission requirements in a timely fashion. It is a busy site with operational rates peaking at values between 60-120 operations per hour, and requirements for landing operations alone at these levels for short periods as multi-helicopter flights arrive.

Conditions of low visibility and ceiling prevail around the site, although not necessarily in other areas. The ATM/C problem is to provide safe air traffic separations between arriving and departing helicopters, to define flight paths and provide guidance along these paths if necessary, and to establish the sequence and schedule for landing and departure pad operations. From the pilot's viewpoint, the problem can be broken into five interrelated phases of flight: Phase 1 - Arrival; Phase 2 - Approach Spacing; Phase 3 - Final Approach; Phase 4 - Transition and Ground Taxi; and Phase 5 - Departure.

3b. Phase 1 - Arrival

Although there will be some flight plan data communicated from other ATC sectors, it can generally be assumed that the arrival of helicopters into terminal airspace resembles a random arrival process. To enable the

ATM/C system to convert this random set of arrivals into a regular, well spaced set of arrivals at the landing pads, it is necessary to obtain contact with arrivals at a time before touchdown of the order of ten minutes (or at a radius of roughly 15 nautical miles). This is the boundary of terminal airspace. Its radius depends upon the maximum landing rate expected. At these boundary points, communication is established and surveillance data on helicopter position, ground speed, and direction should be available to the ATM/C system.

It is possible to estimate the number of helicopters in the ATM/C system as a function of operational rates. For example, if initial contact is made 10 minutes before touchdown and the landing rate is 60 per hour, then there will be an average of 10 landing aircraft in the system, but there may also be peaks of the order of 20. If we extend the area or increase the landing rate, these numbers will increase. However, note that multi-helicopter flights can be treated as one arrival entity in the early parts of this phase before being spaced for individual or paired approaches.

The number of helicopters in the arrival phase can be controlled by the "Metering" function. Knowing the traffic flow capacity of the final approach element, arriving flights may be asked to circle or hold at their entry points such that the entry flow matches the landing flow, and such that the approach spacing process does not become oversaturated with too many helicopters.

Since there is a need to keep arrivals and departures separated in the terminal area airspace, it is efficient to combine the Arrival and Departure phases into one ATC control sector. Note that if the departure rate equals the arrival rate, there will also be an equal number of departing targets on the terminal area radar display.

Arriving helicopters are "vectored" from their entry points towards the approach spacing area downwind from the final approach. Vector commands consist of rough heading and speed commands, as well as step descent commands towards initial approach altitudes. These commands could be data linked for display to the pilot, who then must acknowledge the command. At present, one radio frequency is usually dedicated to the arrival phase, and another to the departure phase in a high density terminal area for civil operations.

3c. Phase 2 - Approach Spacing

As helicopters arrive, information is passed immediately to the "Scheduling" function which determines a tentative sequence and scheduled times for pad operations, and therefore arrival times at the entry to final approach. Planned flight paths can be automatically generated to deliver helicopters free of conflicts with other arrivals or departures. As new arrivals occur, this tentative schedule will change to achieve efficient operations, or to accommodate emergencies. Multi-helicopter flights are separated for individual approaches, or perhaps paired approaches if visibility conditions permit.

The spacing is accomplished by heading and speed commands within the coverage of the Microwave Landing System (MLS). These commands can be transmitted by data link to the pilots (or autopilots). If radio communication is used, it is likely that a separate frequency will be necessary to ensure that timely commands can be issued. Thus, the pilots would have to switch radio frequencies to enter the Approach Spacing phase. The final heading would be the inbound approach course directly towards the landing pad. There may be two or three nominal final approach courses if the azimuth

coverage of the MLS is sufficient, and there are no terrain clearance problems at the site. The output of this phase is properly spaced helicopters at a specified initial approach speed for their DSAL.

3d. Phase 3 - Final Approach - DSAL

Given that the metering, sequencing, spacing, and scheduling functions have been accomplished in Phases 1 and 2, there is a flow of spaced arrivals into the various final approach paths. Now, the primary objective of the pilot is to carry out the precision guidance tasks of DSAL: tracking the specified inbound localizer course; capturing and tracking the specified glide slope; initiating and carrying out the deceleration. All of these are performed under IMC conditions using a flight director, or automatic flight control system.

It is assumed that entry speeds to DSAL are in the range of 60-90 knots, and glide slope angles are in the range of 6-9 degrees. The deceleration point is 0.5 to 1.2 nautical miles from touchdown (or 1.0 to 1.5 minutes), and the glide slope is 330 to 1120 feet above the pad at this point. Depending on the entry speed and altitude, helicopters may first encounter either the glide slope or the deceleration point.

Since the pilots are occupied with the DSAL guidance task, the ATM/C system monitors the actual separations between successive helicopters, and commands a missed approach when safety standards are violated. The distance separations are time varying and complex, although time separations remain constant. For example, two helicopters with entry speeds of 60 knots, separated by 1 minute, have a distance separation of 1 n. mile before DSAL, a separation of 0.9 n. miles when the first helicopter is transitioning to visual flight, and a separation of 0.5 n. miles when the first helicopter

is landing. For helicopters with different entry speeds, and for different desired time separations, the nominal distance separations required make the monitoring task impossible if only distance separation is displayed to the controller.

The exit from DSAL is a transition to visual flight which occurs at least 25 to 35 seconds before touchdown at ranges of at least 300 to 1000 feet and speeds above 20 to 35 knots. These depend upon decision criteria for visual landing assumed to be of the order of 50 to 100 feet in height, and 500 to 1000 feet in visual range.

This DSAL phase is considerably different from the approach phase for fixed wing aircraft where a fixed approach speed as measured in terms of airspeed is maintained. The deceleration phase occurs below 400 feet where the helicopter is in the earth's boundary layer. If strong winds are present, they will vary in strength and direction during the deceleration phase, and these disturbances will affect the helicopters in greater or less proportion since they are at different airspeeds. However, the DSAL is based not on airspeed but on range rate. The dynamics of the flight director cues (or the automatic flight control system) determines how the helicopters respond to disturbances, and thus will affect the variations in time of arrival at the landing pad.

3e. Phase 4 - Transition and Ground Taxi

At some height and distance from touchdown, the pilot transitions to visual flight, and assumes manual control of the helicopter for the final deceleration and transition into air taxiing. If helicopters do touchdown, it will be necessary to maintain a forward ground speed across the touchdown zone, and directly into a taxiway since at landing intervals of one minute

(or perhaps 30 seconds) the touchdown zone cannot remain occupied for very long. It is desirable to assist the pilots during transition by supplying various forms of visual guidance. Approach lighting and visual approach guidance systems will assist in the final stages of the decelerating approach, and pad lighting and taxiway centerline lighting with different colors for guidance on different taxi paths can assist in touchdown and pad clearance.

Pilots will receive landing clearance and pad clearing taxi instructions simultaneously. Assignment of parking spaces may affect taxi instructions, and will be done efficiently so the taxiway system can accept arrivals without blocking the landing pad. There will be missed approaches suddenly called by pilots in this transition phase. The ATM/C system will provide a means of ensuring that they do not interfere with helicopters lifting off the departure pads.

3f. Phase 5 - Departure

At a high departure rate, it is necessary to schedule the departure flow. Pilots calling departure control from parking spaces will be given taxi clearances so as not to interfere with the landing taxi flow, and may be given a time for taxi so as to prevent a long line of helicopters awaiting departure. After lift off, there may be a small set of Standard Instrument Departure paths to be followed. These will specify altitude and headings, and may use radio beacons, or other navaids placed in the surrounding area to ensure good navigational accuracy. The ATM/C system is responsible for separation assurance between successive departures, as well as between departures and arrivals in the terminal airspace. There will be surveillance coverage at low altitudes for departing traffic.

3g. Kinematics of Delecerating Steep Angle Approach and Landing

The major difference of a terminal area ATM/C system designed for Army helicopters is the capability of performaing a final deceleration in airspeed under IMC during the final stages of the approach. This section describes the kinematics of the DSAL to establish some bounds in designing a terminal area ATM/C system which accommodates this operational capability. Appendix 1 provides the simple kinematic equations, and various tables of results in applying them.

It is assumed that the nominal constant deceleration rate is 0.05 g which is roughly 1 knot/second. The equations are then written in terms of t (time to hover) for reasons of simplicity. For every t, there is a nominal range to touchdown on the DSAL profile, so that the results could easily be converted to a distance based tabulation.

The parameters in DSAL operations are: Glide Slope angle, α; Landing Interval, Δt; and Decision Height, DH, or Decision Range, DR. The results in Appendix 1 have been tabulated for $\alpha = 3,6,9$ degrees, for $\Delta t = 30,45,$ 60 seconds, and DH = 50,100 feet, or DR = 500,1000 feet. These values should bound the normal range of DSAL operations. The tables in Appendix 1 give range, range rate, altitude, altitude rate, and range separation at various points on DSAL. Range separation is the distance to the following helicopter assuming it is also on DSAL (which may not be true).

Examination of the results of Appendix 1 can be summarized. First, the range separations when a helicopter touches down can be very small. For a landing interval of 30 seconds, the following helicopter will only be 725 feet from the pad. For Δt = 45 seconds, the following helicopter will be 1630 feet away, and for Δt = 60 seconds, it will be 2898 feet. However,

that assumes that a full deceleration to a hover occurs, whereas to keep the landing pad clear, helicopters should decelerate only to air taxi or ground taxi speeds.

If the range from touchdown at the Decision points are examined in Table 3, Appendix 1, it is seen that for $\Delta t = 30$ seconds, the following helicopter usually will have reached the decision point and will be visual before the first helicopter reaches the pad. Thus, it will not receive landing clearance before becoming visual. For $\Delta t = 45$ and 60 seconds, the opposite is true. When the following helicopter reaches minimums, the pad will be clear, and landing clearance may already have been given. Of course, at higher visibilities, these following helicopters may become visual and see the preceding helicopter on its final approach.

The critical separation point for DSAL is probably that between the helicopter at the Decision point and its following helicopter since both may be under IMC. Table 3 in Appendix 1 shows that separations here are of the order of 2000 feet for $\Delta t = 30$ seconds, of 3000 feet for $\Delta t = 45$ sec., and of the order of 1 n. mile for $\Delta t = 60$ seconds. For the latter case, the following helicopter may not have commenced deceleration if its entry speed is below 75 knots.

If the use of an airborne collision warning system were to be considered for DSAL, the value of τ (time before collision, derived in Appendix 1) is of interest. The expression shows that if both helicopters are on DSAL, τ is always $\Delta t/2$ beyond the time at which the first helicopter will reach the pad. This may provide a method for ground monitoring of separations on DSAL, and establishing a simple separation standard for declaring a missed approach.

The conditions at entry to DSAL are displayed in Table 2 of Appendix 1 as a function of entry speeds between 60 and 120 knots. At 60 knots, the deceleration point is 3185 feet and 62.9 seconds from touchdown. At 90 knots, it is 7158 feet and 94.3 seconds from touchdown.

Pilot workload creates a desire to separate this deceleration point from the glide slope capture point when DSAL is flown manually with a flight director. This places restrictions on the altitudes and speeds which the ATM/C system can select. The changes in pitch and altitude rates at glide slope capture are rather high, particularly for the steeper glide slopes and higher entry speeds. For example, at 90 knots and 9 degrees, the helicopter pitches down 9 degrees to transition from level flight to 1425 feet/minute descent. It is advisable to accomplish glide slope capture first, and then begin deceleration after acquiring the glide slope at constant speed. This means that there is a minimum entry altitude for every entry speed for flight director approaches. For example, Table 2, Appendix 1, shows that for 75 knots and a 6 degree glide slope, the deceleration point is at 519 feet altitude, and the altitude descent rate is 794 feet per minute. If we allow 20 seconds to capture the glide slope before reaching the deceleration point, the altitude for entry will be $519 + [\frac{20(794)}{60}] = 784$ feet.

Alternatively, the altitude could be below 519 feet so that the deceleration point occurred first. For example, if the entry altitude was 332 feet, the 6 degree slope would be captured at 60 knots at 15.7 seconds after the deceleration point. Now, the initial altitude rate required is 635 feet/minute (at 332 feet above the pad) and is continuously decreasing as the forward speed is decreased. This alternative low level approach requires coverage by the MLS at altitudes of 332 feet and ranges in excess of 7158 feet from the site, or well less than 3 degree elevation.

SECTION 4

A PROPOSED ATM/C SYSTEM AND PROCEDURES

A very specific ATM/C system and set of IMC operating procedures is now constructed to act as a "strawman" and illustrate the problems and needs in developing a new system. It adopts the controller's view of operations, and concentrates on ATM/C functions for the landing traffic.

Figure 1 shows the general geometry of a terminal area. Suppose there are four entry points (A,B,C, and D) which are not all equidistant from the landing pad. There may be a low power radio beacon at these points. It is assumed that arrivals contact the ATM/C system, and come under surveillance before entering the terminal area. Some arrivals are expected since flight plan data may be forwarded from other ATC control sectors, but positive identification and a good ETA (expected time of arrival at the entry point) will not be available until first radio contact and establishment of surveillance. As a standard procedure, all arrivals conform to a standard entry airspeed of 90 knots in the "strawman" system. This allows the expected time to fly from an entry point to the landing pad in the absence of traffic to be estimated. With a good ETA for the entry points, then ETAP (estimated time of arrival at the landing pad) can also be estimated for every arrival.

4a. Metering

In the strawman system, an automated "Metering" function exists. It is a very simple function, but does require some computer automation and display interfaces with the controller to assist him in establishing a landing sequence, in establishing MTAP (metered time of of arrival at pad),

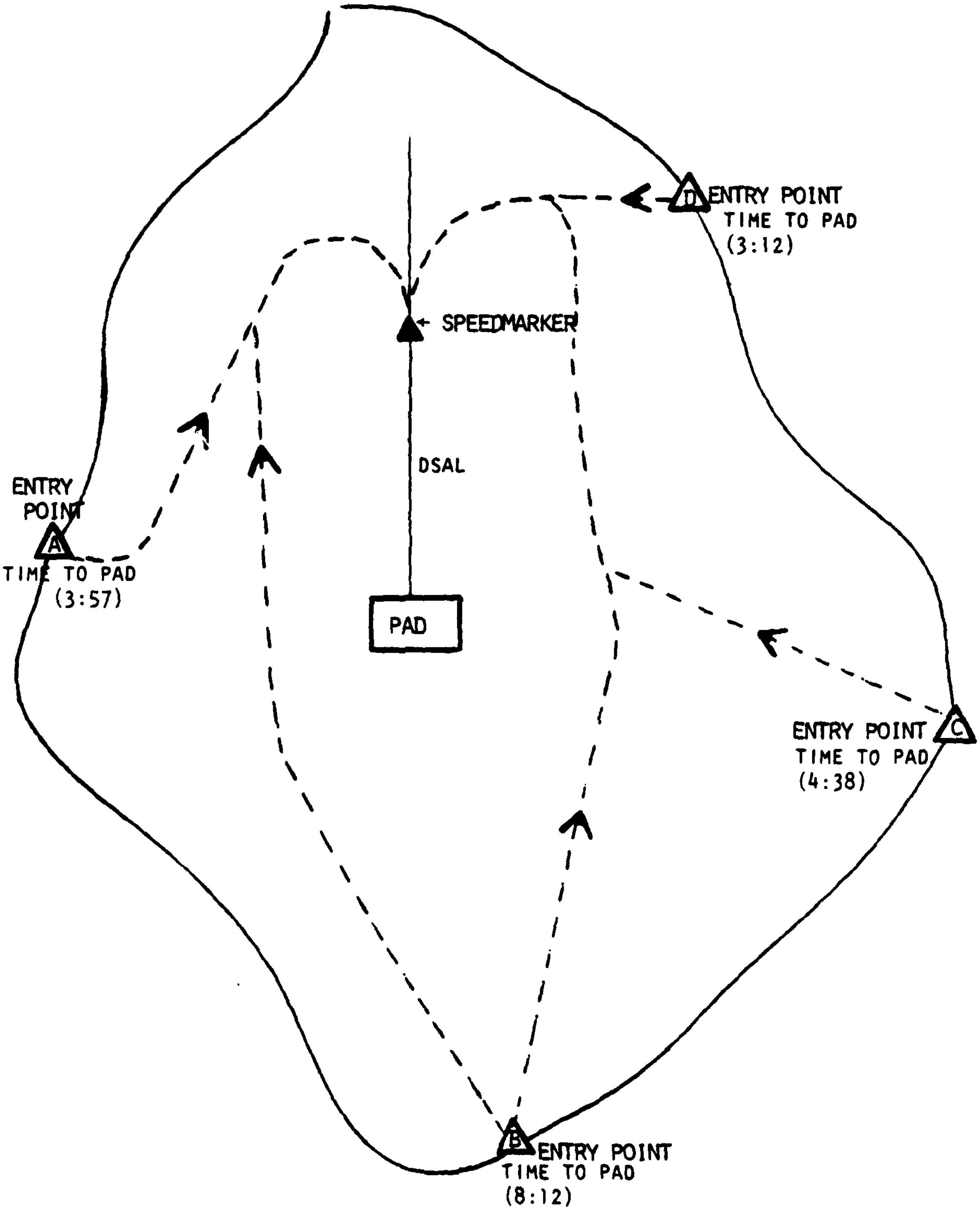

FIG. 1: TERMINAL AREA GEOMETRY

and in issuing "holding" commands at the entry points if necessary. These holding points would be in areas protected from enemy observation.

For example, suppose the pad controller is running the landing pad at 30 second intervals. The entry controller establishes radar contact with arrivals using VLATME (very lightweight air traffic management equipment) or some such surveillance equipment. With tracking established, each identified arrival will have an ETA at the entry point. Given the current winds, and the commanded air speed of 90 knots for flying within the terminal area, a nominal ETAP can be calculated for arrivals at each entry point.

As helicopters arrive, their landing sequence can be "first come - first served", based upon ETAP values. Thus, an arrival at B may contact the entry controller first, but his ETAP may make him follow an arrival at D who subsequently contacts the controller. If we envisage digital data feeding a small computer, all arrivals can have their ETA's and ETAP's automatically computed, and a list of properly sequenced landing arrivals can be displayed to all controllers.

But the metering function can now go further in producing a schedule of pad arrivals and the delays which are necessary for each arrival. The size of the required delays may trigger a command for holding at the entry point at an assigned altitude.

An example list is shown in Table 1. Given the ETAP values, and a $\Delta t = 30$ seconds for landing intervals the automated metering function computes MTAP. In the table, RED 76 and 77 arrive simultaneously at Point B at 1402:25. The metering function assumes they are going to fly independent approaches 30 seconds apart so that RED 77 is delayed by

TABLE 1

THE METERING LIST OF ARRIVALS

LANDING INTERVAL = 30 SECONDS

HELICOPTER IDENT.	ETA	PT.	ETAP	MTAP	HOLD DELAY	HOLD?
RED 76	1402:25	B	1410:37	1410:37	0	No
RED 77	1402:25	B	1410:37	1411:07	0:30	No
BLUE 01	1406:41	A	1410:38	1411:37	0:59	No
GREEN 13	1407:29	D	1411:01	1412:07	1:06	No
AMBER 07	1406:50	C	1411:20	1412:37	1:17	No
AMBER 08	1406:50	C	1411:20	1413:07	1:47	No
GREEN 14	1408:20	D	1411:32	1413:37	2:05	360°
RED 81	1406:45	B	1414:57	1414:57	0	No
(etc.)						

30 seconds. This will be easily accomplished enroute from Point B by path stretching. Four minutes later BLUE 01 arrives at Point A, but because of his short time to the pad, his ETAP is almost coincident with RED 77 and 78. But since he is judged to be 1 second later, his MTAP is 30 seconds after RED 77, and he must be delayed 59 seconds. The metering function considers that this can be accomplished by "path stretching" enroute from A, so that no holding is called.

GREEN 13 will arrive at D about 1 minute after BLUE 01, and with an ETAP spaced 23 seconds after BLUE 01. But since BLUE 01 is going to be delayed 59 seconds, GREEN 13 must now be delayed 66 seconds. Again no holding is necessary.

AMBER 07 and 08 will arrive at Point C about 30 seconds prior to GREEN 13, but because of their longer transit time, their ETAP is 19 seconds after GREEN 13. AMBER 07 is delayed 77 seconds, and AMBER 08 is delayed 107 seconds. No holding is called.

GREEN 14 will arrive at D at 1408:20 with ETAP of 1411:32, and MTAP = 1413:37. It will be delayed more than 2 minutes, so a 360 degree turn at D is called as a holding maneuver.

RED 81 will arrive at B almost 2 minutes ahead of GREEN 14's arrival at D, but his ETAP is 1414:57 which will be his MTAP since GREEN 14 will have arrived at the pad 80 seconds earlier. Thus RED 81 has no delays in arrival.

This brief example provides an insight to the metering function and, hopefully, the value of automating it for the entry controller when high landing arrival rates are occurring. While it is computationally or logically simple, it will require careful software development and testing.

It is advisable to gain some operational experience with it in a real time ATC simulation environment since the real time and human factor aspects of controller interaction with the displays and the computer function need to be explored. Some method of handling missed approaches, and providing priority handling of low fuel state or battle-damaged aircraft, and change of approach path if the pad is blocked must be developed.

4b. Final Approach Path Geometry

The geometry of the area for approach spacing and the final approach paths is considered next. It is assumed that some form of MLS exists which can provide accurate guidance, and also surveillance (perhaps using the crossbanded technique described in Ref. 3). A possible geometry for three straight approach paths is shown in Fig. 2. The MLS is located 2000 feet behind the landing pads which are then separated by 1000 feet. For the same landing rate, the longitudinal separations used on a given approach path can be tripled, thereby easing the requirements for precision spacing.

Notice that at localizer capture under radar vectoring control, the helicopters will be separated laterally by roughly 10,000 feet. As the helicopters follow their localizers, the lateral separations reduce to roughly 3000 feet at the initiation of DSAL, and finally to 1000 feet at the landing pad. These distance separations are better than those at $\Delta t = 30$ sec. intervals on a single path, and it is unlikely that helicopters will be arriving exactly at the same time. Thus, there will generally be lateral plus longitudinal spacing, and errors in longitudinal spacing are not as critical.

If the MLS azimuth coverage is reduced, a dual approach path system may still be possible. The geometry may not be feasible at every site. Terrain

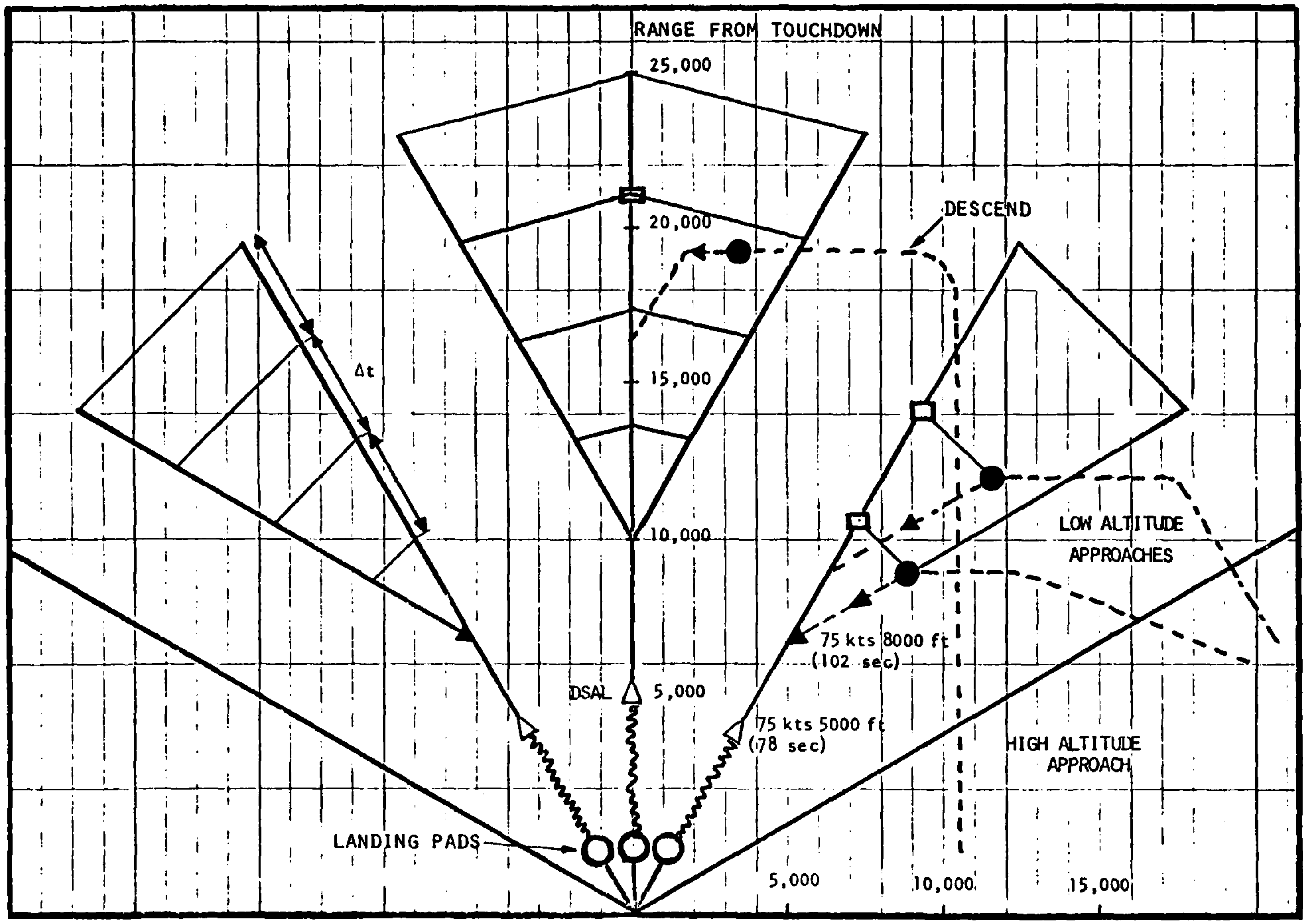

FIG. 2: MULTIPLE APPROACH PAD CONFIGURATION - DISPLACED PAD AND GLIDESLOPE

clearances must be provided under each localizer, and the MLS must be located 2000 feet behind the multiple pads. This rearward location would mean that the parking revetments are between the MLS and the pads. Thus, parking may have to be located to either side to avoid multipath reflections for these multiple approach configurations. Some analysis of taxiway and parking operations would be required.

The missed approach paths for these multiple approaches seem straightforward. For the center localizer, helicopters climb straight ahead, passing over the pads and localizer before turning left or right under radar vector control. The other cases turn outwards from the center by 60 degrees and climb. It is difficult to locate departure pads which do not interfere with these missed approach paths.

The radar vectoring and entry into the radar vectoring area is complex but not difficult. As shown in Fig. 2, altitude separations of 500 to 1000 feet can be used to reach the center vectoring area. As shown, the two other approach paths are low level with the center at higher level, but this can be reversed. As shown, aircraft overfly the lower vectoring areas, and descend into the center area if necessary. Normally, aircraft from different entry points will use the most convenient approach path. Notice that the metering function now must also select the approach path, and compute the ETAP differently for each path. Each pilot would be told of his final course direction so that he could set the course select knob of the flight director. The flight director or Autopilot would be programmed for a final 30 degree intercept as called for in the geometry shown. Then, the pilot could be cleared for the approach at the appropriate time by the spacing controller, and simply go to LOC mode on the flight director or autopilot at that time.

4c. Precision Spacing and Speed Command

If dual or triple approach path geometries are not possible, the achievement of higher landing rates requires much smaller longitudinal spacings on the single approach path. This greatly increases the requirements for accuracy in position measurement and tracking performance of the surveillance system in the approach spacing area. If radar vectoring can achieve spacing accuracies of ± 10 seconds or better, then we can use a "Speed Command" to achieve the very precise spacings in time and distance required for a single DSAL approach path. Notice that at 90 knots ground speed, the distance spacings are 9114 feet for $\Delta t = 60$ seconds, and 4557 feet at $\Delta t = 30$ seconds where Δt is the desired landing interval. These distance spacings are well below the 3 n. miles or 18240 feet used in civil practice, and they compress into much smaller distance separations during DSAL.

But unlike civil practice, we can control the speeds of the helicopter. In particular, if we are in the coverage of an MLS system, and ground traffic control can obtain range and range rate on approaching helicopters, we can command a speed reduction which will achieve a decrease in the dispersion amongst time intervals for entry to DSAL and for landing.

Figure 3 shows a possible geometry where the final vectoring area is farther away from the landing pad so that a constant, straight-in approach path of 30 seconds can be inserted, plus a "Speed Command" called in the following 60 seconds before DSAL entry. The straight-in segment is required to establish good tracking in range and range rate to determine the Speed Command and its timing. A nominal approach would reduce to a range rate of 75 knots at a constant 0.05 g deceleration at a "Speed Marker" point 14690 feet from the pad, and then fly at 75 knots range rate for 60 seconds

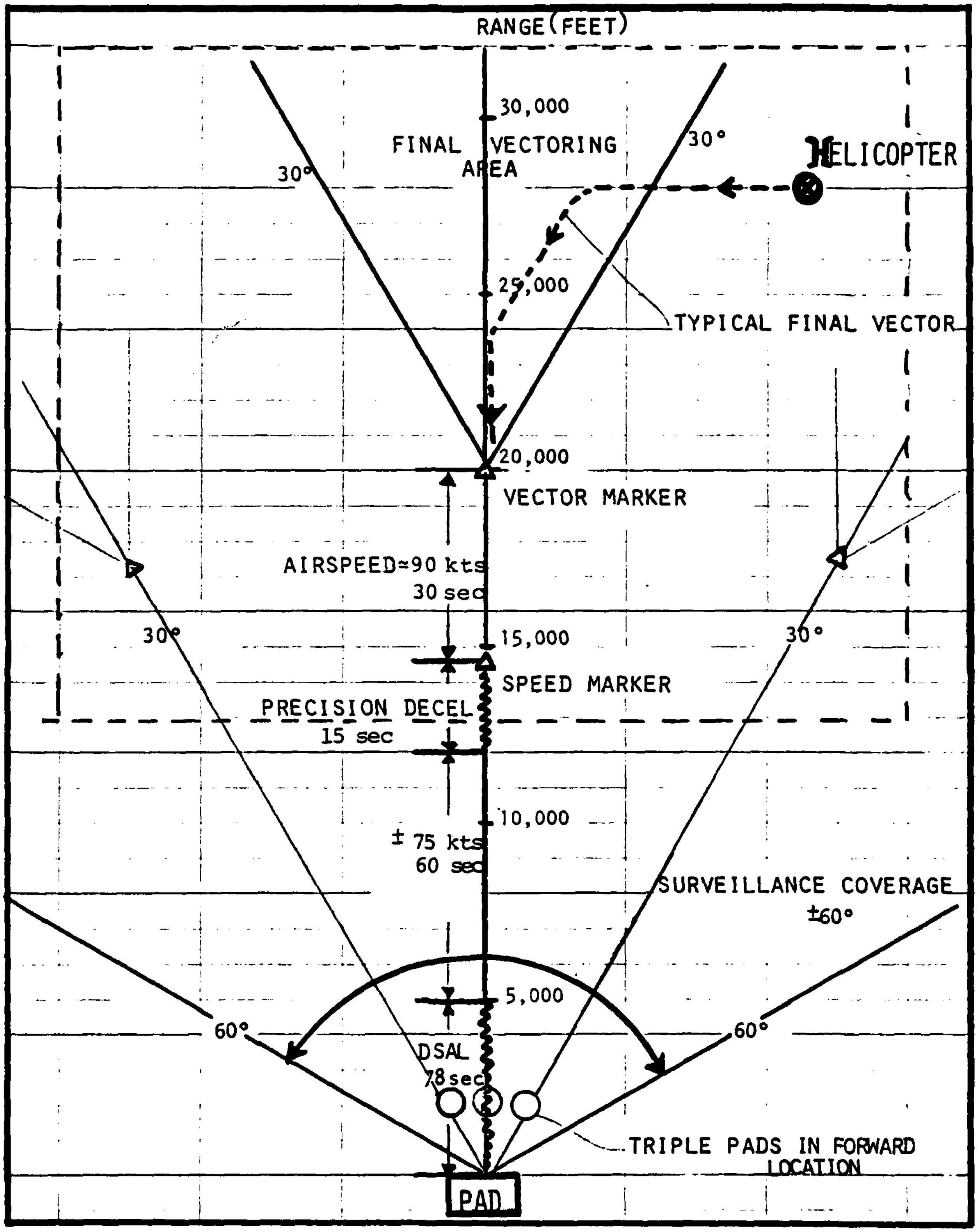

FIG. 3: GEOMETRY OF EXTENDED FINAL APPROACH VECTORING AREA

before intercepting the usual DSAL profile. By knowing the range and range rate, this "Initial Approach Speed" command would always be called at the "Speed Marker", and could be adjusted from 90 to 60 knots, to obtain precision spacings between successive helicopters. The spacing intervals in this example can be closed by 10 seconds, or opened by 16.5 seconds by means of this speed command. The residual dispersion depends on timing of the command and the guidance provided to the pilot or autopilot in carrying out the speed command.

Figure 4 shows the profiles associated with this example. The top diagram shows range rate versus time to hover. Points M_1, M_2 and M_3 are the "Speed Command" times for the 90, 75 and 60 knot initial approach speeds. These are labelled, respectively, profiles 1, 2 and 3. The separation in time between M_1 and M_3 shows the range of adjustments which are possible. The bottom diagram shows range versus time for the three profiles.

This method of obtaining precision spacing envisages that good information on range and range rate for successive helicopters is available to a ground control system. If available in digital form, the desired "Initial Approach Speed" could be displayed to the pilot, or sent directly to the autopilot or flight director. In essence, the DSAL profile has been extended by roughly 60 seconds, and is now variable within the bounds of profiles 1 and 3.

While there is a possible deviation of -10 to +16.5 seconds from the nominal profile, it should be remembered that this size of adjustment will not be available for every successive pair of helicopters. If the first helicopter has been assigned to profile 3 which has a 60 knot initial approach speed, then we cannot supply any "plus" spacing to a second

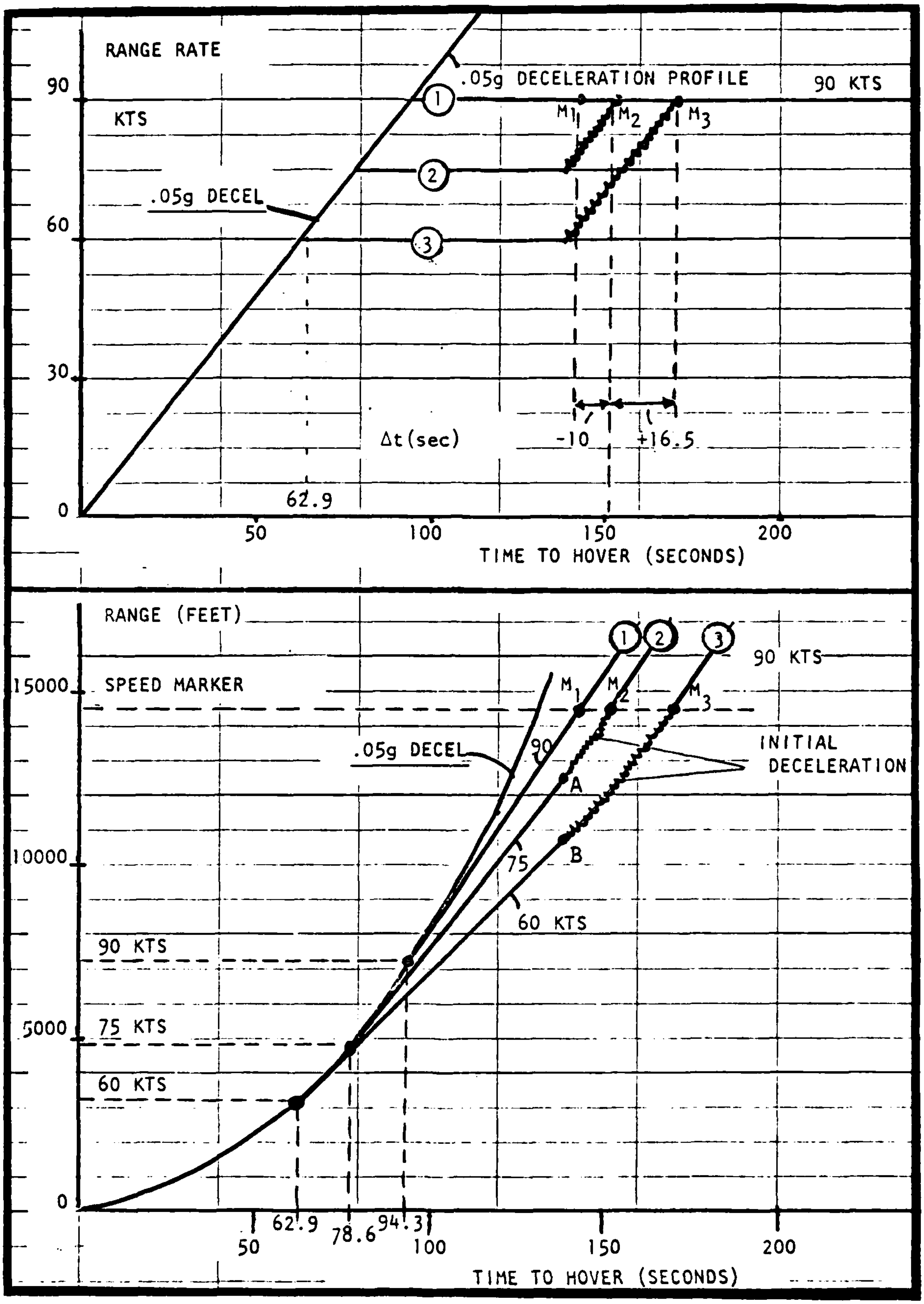

FIG. 4: SPEED CONTROL FOR PRECISE SPACING

helicopter which is early. Thus, the radar vectoring still has to produce good spacings at the Speed Marker on the average. Proposals for computer-aided vectoring will be described later. Note that the precision spacing speed adjustment is possible on most arrivals.

4d. Monitoring Separation on the Extended DSAL

The strawman ATM/C system is capable of monitoring the actual separations between successive helicopters on the DSAL, and providing separation assurance to pilots under IMC. The concept of controlling the deceleration rate to maintain separations was considered and rejected. Instead, the strawman system provides precise spacing at entry, and allows the DSAL to be flown without any control. Appendix 2 describes a mathematical model which determines the probable separation errors at the pad. It indicates that the dispersion in pad arrival times will not be much larger than that at entry given expected variances in times to fly the DSAL. This model is a necessary link in determining precision spacing requirements as a function of separation violations on approach (and therefore, the rate of missed approaches called by the ATM/C system).

In the strawman system, good tracking is established prior to calling the Speed Command. Tracking provides range and range rate which are required by the ATM/C system to monitor separations between successive approaches. The quality of information in these two quantities creates requirements for good dynamic tracking performance for the surveillance system on targets which are deliberately going to be decelerated. In the strawman system, knowledge of the Speed Command and DSAL are used in the tracker processing to obtain good dynamic performance.

Given good information on range and range rate, the strawman ATM/C system displays information for the controller to assist him in monitoring separations on the extended DSAL. The desired separation is time varying because of the two decelerations. The desired position of each helicopter on DSAL can be displayed as a box of dimensions such that whenever the helicopter is determined to be outside the box, it raises the issue of calling a missed approach.

But, the system also displays an estimate of the actual landing intervals, Δt_{12}, between successive helicopters based on their actual range and range rates. Thus, two successive helicopters can both be late, but have a proper landing interval. Consequently, the decision might be to call a missed approach for a third helicopter which actually is within his approach box. As well as displaying this information to the controller, the strawman ATM/C system provides computer aided decision support in determining which helicopter should be called to minimize the number of missed approaches. When a missed approach is declared by the human controller, it is immediately displayed to the departure controller to avoid any conflicts.

4e. Computer Aided Vectoring for Initial Approach Spacing

Prior sections have covered the final approach precision spacing and separation monitoring, and also the metering of the initial entry of helicopters into the terminal area. It is now necessary to deal with the missing portion where metered arrivals are vectored onto the approach centerline at correct time spacings. The dispersion in these "Initial Approach Spacings" may be the critical element in achieving a high rate of landing with safety.

In the metering function, it was assumed that a common 90 knot airspeed would be flown by all helicopters in this phase of flight. Then the flight

path is controlled by issuing heading vectors which keep arrivals safely separated from other arrivals and departures, and which finally direct the helicopter into its "Slot" or "Box" on the approach centerline. This "Box" will "fly" a nominal DSAL profile to arrive at the pad at the MTAP determined by the Metering function. At high landing rates, the human controller will need to be assisted by computer generated "final vectors" which determine the initial approach spacing. However, the controller retains control responsibility and remains "In Command" of the situation. The use of computer aids raises the need for analysis of the human factors problem of the controller's real-time interaction with the computer display.

Figure 5 shows a format for a display for the Initial Spacing Controller. It corresponds to the dotted rectangular outline shown in the geometry of Figure 3. From the Vector Marker, two 30 degree radials define the vectoring area, and the final intercept vector has been selected at 30 degrees to the centerline. At the top there are two ±15 degree boundary lines within which targets will be vectored. Horizontally across the top of the display, there are boxes representing arrivals from the right or left, with the landing sequence number inside. These sequence numbers and the landing schedule have been determined by the Metering function. These boxes move towards the centerline, and then down the centerline at an airspeed of 90 knots in sequence and properly spaced. At this time, the box expands to a size which indicates the maximum tolerable error expressed in seconds which has been selected, and grows a 15 degree "Wand" to the left or right. The corresponding target is vectored to stay below this "Wand" until it is within the final vectoring area. When the wand touches the target, the final vector to a 30 degree intercept heading is called (the explanation for

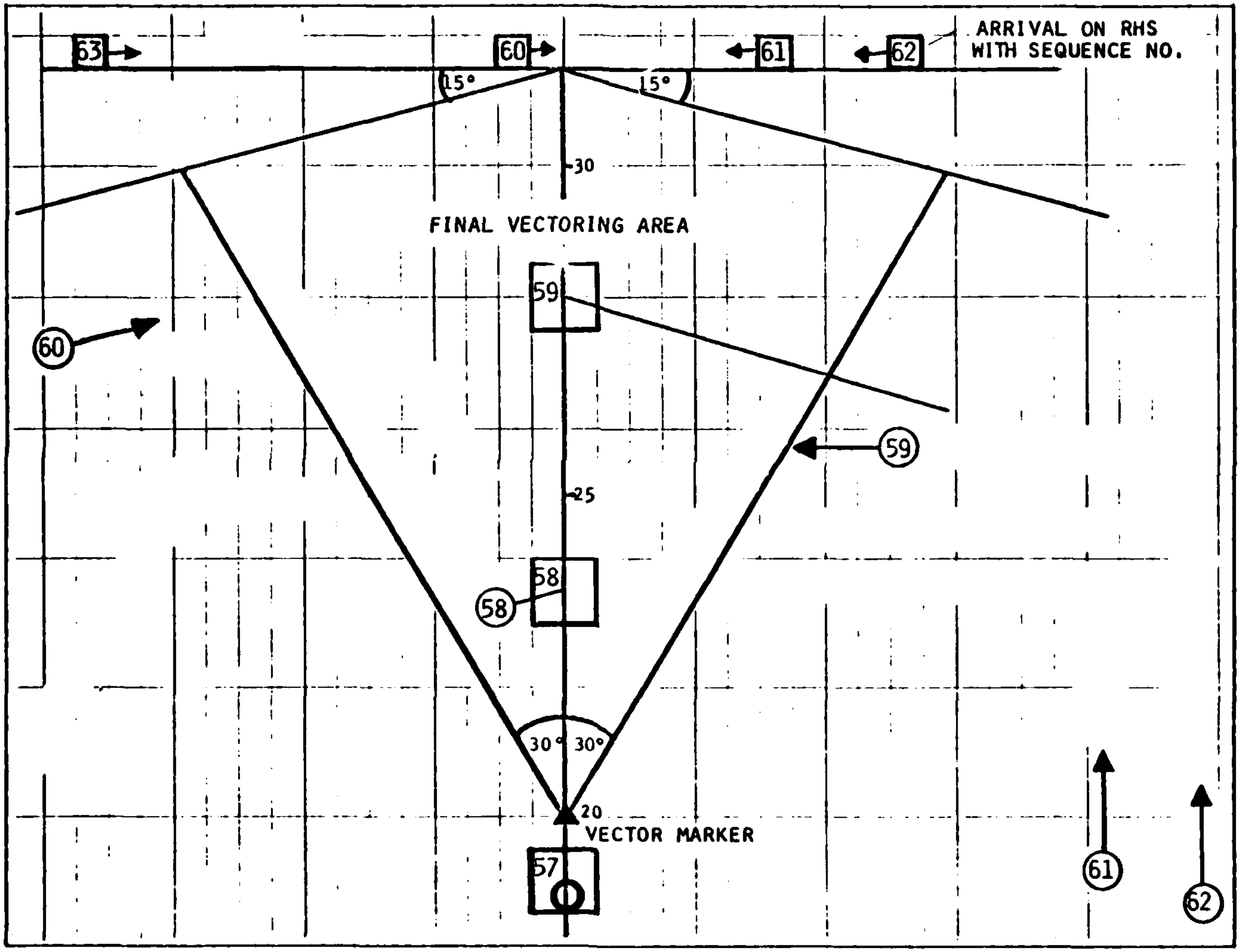

FIG. 5: DRAFT DISPLAY SCHEME FOR FINAL VECTOR CONTROLLER

this is given in Appendix 3). If performed prop.rly, the box and target will intercept on the centerline at some point before the Speed Marker. Both the previous vector (to get within the final vectoring area) and the final intercept vector can be passed on to the pilot/autopilot via a digital data link. The human controller accepts metered arrivals and vectors them with proper separations into the final vectoring area. It is advisable to consider real time simulation of this control process at high landing rates, both to investigate the workload on the Initial Spacing controller, and to study the human factors problems of the real time display.

Notice that the initial spacings are established by the boxes and the metering function. The spacing errors are displayed from a nominal position, and used to compute the desired precision speed command. These errors are uncorrected as desired by the Precision Speed Command.

The Initial Spacing controller can select the landing rate, the final vector heading, and the box size. There would probably be a secondary computer display which would provide an "Arrival List" giving pertinent data on the arrival helicopters rather than add a list of alpha-numeric data to the format of Fig. 5.

4f. Summary

The strawman ATM/C system proposed in this section is only one of many systems which can be created to meet the needs of the US Army. The various general ATM/C functions discussed in Section 2 (Separation Assurance, Scheduling, Spacing) can be implemented in various degrees of automation, and assigned to the controllers in varying ways. Deficiencies in Surveillance and Tracking, Communications, and Computer Display and Automation may be overcome to some degree by designing around them.

The specification of the maximum landing rate is a key performance parameter in designing an ATM/C system. As it is increased, it narrows the range of alternative ATM/C systems and increases the requirements for technological capabilities. It is possible to create an evolutionary plan for developing a series of terminal area ATM/C systems which have increasing levels of performance and functional capabilities as higher performance sub-system technologies are introduced.

SECTION 5

DEFINITION OF PROBLEMS AND RESEARCH NEEDS

5a. Determination of Operational Requirements

There is a need for the US Army to establish the basic System Operational Requirements for the terminal area ATM/C system. In particular, the desired landing rate for the system needs to be determined, since most of the requirements in surveillance and tracking, communications, and computer automation are strongly dependent upon it. In this study, it is only possible to suggest that a landing rate of approximately 15 per hour for the current operational GCA (Ground Controlled Approach) system is inadequate, and that a landing rate of 60 per hour is probably required by future operational scenarios. Establishing a safe landing interval of 1 minute would be a suitable initial goal since it would appear that an ATM/C system with this performance can be developed from technologies already available[3] assuming normal civil standards for separation assurance. At smaller landing intervals (or higher landing rates), surveillance systems with greater precision and tracking performance, and communication systems of greater speed in transmitting commands and guidance data will be required. This would necessitate further systems analysis, and research and development to generate the required technologies.

The determination of basic SOR's is a necessary first step to guide both development and research for an ATM/C system. The Army, with full knowledge of its plans for future combat operations under IMC, must establish goals for landing rates and any other operational requirements for the ATM/C system.

5b. Definition of Surveillance and Tracking Performance Requirements

The surveillance requirements divide into three categories. The arrival and departure phases of operation (as described in Section 2) create a requirement for low level, low precision surveillance over an area 15 n.miles or more from the landing site. This "Area" surveillance has horizontal position accuracy requirements of the order of $\sigma = \pm 100$ m, and vertical accuracies of the order of $\sigma = \pm 100$ feet. The tracking requirements for information on speed and direction are not severe unless landing rates above 60 per hour are contemplated, and a full automation of the scheduling and path generation functions are considered.

The second category for surveillance arises in the "Approach Spacing" area. Now, the ATM/C system is attempting to vector a helicopter to a rather precise time "box" on a final approach course. Data on position speed and direction of targets must be of high quality in accuracy and timeliness so that reliable computerized decision support systems can be implemented to assist both in issuing "final vectors" for initial spacing and "speed commands" for final spacing. The requirements would seem to be of the order of $\sigma = \pm 20$ m in position, $\sigma = \pm 1$ m per second in speed, and $\sigma = \pm 5$ degrees in heading. As well, the time lag in such data cannot be more than a few seconds, which creates requirements in terms of update rates. There may be a requirement for a very high update rate over a short period of time as a target approaches critical vector decision point. Since the targets are maneuvering under commands from the ATM/C system, it appears that dynamic tracking performance can be greatly improved by incorporating knowledge of commanded turns and decelerations into the tracking algorithms.

To study the surveillance and tracking requirements for a given desired spacing precision, or inversely, to determine the spacing performance for a given surveillance and tracking system is a difficult problem. It requires a detailed computer simulation of the terminal area ATM/C system with its geometry, target dynamics, wind environment, etc., and also a detailed simulation of the position errors, the update rate (perhaps variable), and the logic of the advanced tracking algorithms. The terminal area ATM/C simulation exists,[8] but the detailed simulation of various surveillance and tracking subsystem performance would require further effort.

The third category for surveillance requirements is the monitoring of actual separations on the DSAL. Now, the flight paths are directed towards the landing pad so that range and range rate are being tracked. The requirements are of the order of $\sigma = \pm 20$ m for range, and $\sigma = \pm 1$ per second in range rate, with a time lag of a few seconds if approach spacings as low as 30 seconds are to be considered. Some specification of an acceptable missed approach rate, and a desirable level of safety or separation assurance are required in determining the approach surveillance requirements. Once again, the inclusion of deceleration commands in tracker logic would improve dynamic accuracy of speed and position data.

5c. Definition of ATM/C System Structure

Further analysis is required to define an ATM/C system given a required landing rate, or an evolutionary series of ATM/C systems for increasing landing rates. The system structure is dependent upon ATC procedures, controller positions and their workloads, automation of decision support functions, interfaces with other ATC control sectors, and the geometries adopted for the terminal areas. For example, it is not clear how many

human controllers would be required to man the strawman ATM/C system. There would be one position for arrival and departing traffic, another for final spacing, another for approach monitoring and pad control for landings and departures. But depending upon arrival and departing traffic flow rates, there could be a congestion problem if radio communications is used which would then require yet another position. Also, the requirements for rapid clearance of the landing pad leads to parking assignment and taxi routing control problems. Further study is needed to establish the geometry of taxiways and parking areas and the methods of controlling arriving and departing helicopters between pads and parking under IMC conditions. The output of work in this area would be the definition of the number of controller positions, their responsibilities, and their display and communication stations. The layout of the transportable ATM/C shelter can then be accomplished.

5d. Definition of Communications Performance Requirements

As indicated in the previous item, the design of the controller positions and communications loadings on communications channels are interdependent. If radio is used to communicate, more controller positions and radio frequencies may be required. For various reasons, the provision of a digital data link must be considered in more depth if a high landing rate system is desired. First, command messages for precision vectoring and for missed approaches are delivered promptly and positively when command timing is important. Secondly, the commands are positively displayed to the pilots. Thirdly, it may allow a reduction of the number of controllers in the ATM/C system. If suitable flight control systems are provided, heading, altitude, and speed commands can be transmitted directly to the autopilots

so that consistent response to ATC commands is achieved for good timing and precision spacing.

5e. Definition of Automated ATM/C Functions

In the strawman ATM/C system, it was suggested that computerized decision support systems and displays be provided for the ATC controllers for the Metering, Precision Spacing, and Approach Monitoring functions. Further definition of these functions and their displays is required, as well as development of prototype software. This can be done within a real time dynamic simulation of the ATM/C system. The human factors problems of working with the displays, and developing controller-in-command relationships with these automation functions needs to be explored so that missed approaches, low fuel state, battle damaged helicopters, and changes of approach paths can be handled.

There may be more than one display per controller. As well as the graphic "situation" displays shown in this report, there is a need for "communication" or "tabulation" auxiliary displays which present the controllers with ATM/C communication information (these replace paper "flight strips" in the present civil ATM/C system).

5f. Definition of Flight Guidance Requirements

The ATM/C system envisaged places some requirements on the Flight Director or Flight Control systems of the helicopters. There may be a need for a display of ATC commands and/or a direct digital command input to the Flight Control system for heading, altitude, and airspeed.

The discussion of transition to visual flight at exit from DSAL in this study indicated the need to determine what pilots can see in terms of approach

lighting patterns particularly if triple approach paths and triple lighting patterns are considered. This may require DSAL flight tests on experiments in a good helicopter flight simulator with external visual scenes in day and night light levels and variable visibility.

Also, the conditions at entry to DSAL present some problems of pilot workload when using a Flight Director. At certain initial speeds and altitudes, acquisition of the glide slope and initiation of deceleration occur simultaneously. Flight tests, or cockpit simulators can be used to obtain pilot assessment of the work load and the deviations from glide slope and speed under these conditions.

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APPENDIX 1

KINEMATICS OF A DECELERATING APPROACH PROFILE

If we define t as the "time to hover", and a as a constant deceleration in range measured from the hover point, we can easily write the equations of motion for successive helicopters on approach. We shall express everything in terms of t, not the range itself, even though that might normally be considered the independent variable for Air Traffic Management and Control due to the normal method of surveillance data display. The equations are:

1. Slant Range, $R(t)$

$$R(t) = \frac{1}{2} a \cdot t^2 = \frac{1}{2} \cdot \dot{R}(t) \cdot t$$

2. Range Rate, $\dot{R}(t)$

$$\dot{R}(t) = a \cdot t$$

3. Range Separation, $\Delta S(t_1)$

We shall use $\Delta S(t_1)$ to denote the difference in slant range between a helicopter (no. 1) which is at t_1 seconds from hover and the helicopter (no. 2) following it at a time separation of Δt seconds.

$$\Delta S(t_1) = \frac{a}{2} \cdot (t_2^2 - t_1^2)$$

$$= \frac{a}{2} \cdot \Delta t \cdot (2t_1 + \Delta t)$$

where $\Delta t = t_2 - t_1$ = time separation between successive helicopters.

If we operate the landing traffic control system with Δt seconds, it will achieve a landing rate of $\frac{3600}{\Delta t}$ helicopters per hour.

4. Altitude Rate, $\dot{H}(t)$

If we assume a constant glide slope with an angle of $\alpha°$, then the rate of decrease in altitude as a function of time to hover is given by,

$$\dot{H}(t) = \dot{R}(t) \quad \sin\alpha = a \cdot t \cdot \sin\alpha$$

5. Altitude, $H(t)$

$$H(t) = R(t) \cdot \sin\alpha = \frac{1}{2} a \cdot t^2 \cdot \sin\alpha$$

6. Time to Collision, τ

$$\tau_{12} = \frac{\Delta S(t_1)}{\dot{R}_2 - \dot{R}_1} = \frac{\frac{a}{2} \cdot \Delta t(2t_1+\Delta t)}{a(t_2 - t_1)} = t_1 + \frac{\Delta t}{2}$$

Table 1. Conditions along Profile

All calculations use 0.05 g = 1.61 ft/sec$^2 \approx 1$ knot/sec

Time to Hover	0	15	30	45	60	90	120
Range, R(t) ft	0	181	725	1,630	2,898	6,520	11,592
Range Rate, $\dot{R}(t)$ knots	0	14	29	43	57	86	114
Altitude, H(t) ft							
Glide Slope = 3°	0	9.5	38	85	152	341	607
6°	0	19	76	170	303	682	1,212
9°	0	28	113	255	453	1,020	1,813
Altitude Rate, $\dot{H}(t)$ ft/min							
Glide Slope = 3°	0	75	151	226	362	456	605
6°	0	151	302	456	605	906	1,211
9°	0	226	453	691	906	1,360	1,813
Range Separation, ΔS(t) ft							
Δt = 30	725	1,449	2,173	2,898	3,622	5,071	6,520
45	1,630	2,716	3,893	4,890	5,977	8,150	10,324
60	2,898	4,347	5,796	7,245	8,694	11,592	14,490

Table 2. Conditions at Entry Points to Profile

Entry Speed (knots)	60	75	90	105	120
Range (feet)	3185	4973	7158	9,758	12,739
Range Rate (ft/sec)	101.3	126.6	151.9	177.2	202.6
Time to Hover (sec)	62.9	78.6	94.3	110.1	125.8
Altitude (feet)					
3°	167	260	374.6	510	667
6°	332	519	748	1,020	1,331
9°	498	778	1119	1,526	1,992
Altitude Rate (ft/min)					
3°	318	397	477	556	636
6°	635	794	953	1,111	1,270
9°	950	1188	1425	1,663	1,901
Range Separation (feet)					
$\Delta t = 30$	3039	3978	4557	5,316	6,078
$\Delta t = 45$	4558	5697	6835	7,974	9,117
$\Delta t = 60$	6078	7596	9114	10,632	12,156

Table 3. Conditions at Exit Points from Profile

Decision Points	DH = 100 ft			DH = 50 ft			DR = 1000 ft			DR = 500 ft		
Glide Slope	3°	6°	9°	3°	6°	9°	3°	6°	9°	3°	6°	9°
Range R (feet)	1910	956	639	952	478	319	1000	1000	1000	500	500	500
Range Rate $\dot{R}$ (knots)	46	33	27	33	23	19	34	34	34	24	24	24
Altitude H (feet)	100	100	100	50	50	50	52	104	156	26	52	78
Altitude Rate $\dot{H}$(ft/min)	246	347	426	174	246	300	178	355	532	126	251	376
Time to Hover	48.7	34.4	28.2	34.4	24.4	19.9	35.2	35.2	35.2	24.9	24.9	24.9
Range Separations												
$\Delta t = 30$	3076	2386	2086	2386	1903	1685		2425			1928	
$\Delta t = 45$	5158	4122	3673	4122	3397	3071		4180			3435	
$\Delta t = 60$	7602	6221	5622	6221	5255	4820		6298			5305	

APPENDIX 2

A MODEL FOR SETTING LONGITUDINAL SEPARATIONS FOR CLOSELY SPACED IMC HELICOPTER APPROACHES

This note describes a model that could be used to determine in a preliminary way, the approximate minimum longitudinal separation requirements between helicopters performing decelerated final approaches with a microwave landing system under IMC. The model is based on a classical problem in Physics involving a random walk by a particle in the presence of an absorbtive barrier. The specific random walk involved here is a Wiener-Levy process.[1] The model has already been used before[2] to determine longitudinal separations between conventional aircraft performing IFR approaches under IMC. The model had to be modified here to account for the fact that in the proposed application with helicopters, decelerated (rather than constant speed) approaches are flown.

The model focuses on two successive helicopters performing an instrument approach in a scenario similar to that described in Ref. 3. At this stage, no wind effects have been included but it is rather straightforward to do so. A nice feature of the model is that its data requirements are minimal, with the main one being the <u>standard deviation of the total amount of time</u> that it takes a helicopter to fly a decelerated final approach under IMC for some specified descent/deceleration profile.

The Model

The two helicopters are viewed as point masses, 1 and 2, that follow (fly) the same one-dimensional path from the beginning of the final deceleration maneuver to the landing point. It is assumed that the two helicopters are supposed to fly identical approach and deceleration profiles and to initiate this approach at the same initial ground speed (e.g., 80 knots). One typical

such approach profile is shown in Fig. 6 of Ref. 3 (reproduced as Fig. 1 on page 3).

Let the separation in time between the two helicopters at the beginning of the final approach be equal to T. Then, under our assumptions, the time separation between the two helicopters would be equal to T at all points of the final approach path under ideal conditions, i.e. if both helicopters flew without the slightest deviation from the prescribed descent/deceleration profile. (The distance between the helicopters would of course decrease as they decelerate.)

We shall now define the quantities:

t_0 = The total time that it takes, ideally, to fly the final approach (84 seconds in Fig. 1).

$t_1(t)$, $t_2(t)$ = The prescribed time from landing of helicopters 1 and 2, respectively, at time t (see Fig. 2). From the definition it is clear* that $t_1(t) + T = t_2(t)$ for all t.

$x_1(t)$, $x_2(t)$ = The deviation (measured in time units) of helicopters 1 and 2, respectively, from their prescribed time positions, $t_1(t)$ and $t_2(t)$, at time t (see Fig. 2). [Without loss of generality, we shall associate positive values of $x_i(t)$, $i = 1$ or 2, with the helicopter running behind schedule, i.e. in Fig. 2, $x_1(t)$ is positive and $x_2(t)$ is negative.]

Using these definitions, the actual separation (in time) between the two helicopters at time t can now be written as:

$$[t_2(t) + x_2(t)] - [t_1(t) + x_1(t)] = [x_2(t) - x_1(t)] + T$$

Our problem is to determine T in such a way that the probability of "collision" between the two helicopters during final approach is very small. To do this we must specify quantitatively the conditions under which a collision occurs and must, therefore, now list the basic assumptions of our model:

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*Note, that in Fig. 2, time is defined "backward", i.e. $t = 0$ corresponds to the time of a helicopter's landing and time $t = t_0$ is the time when the decelerated approach begins.

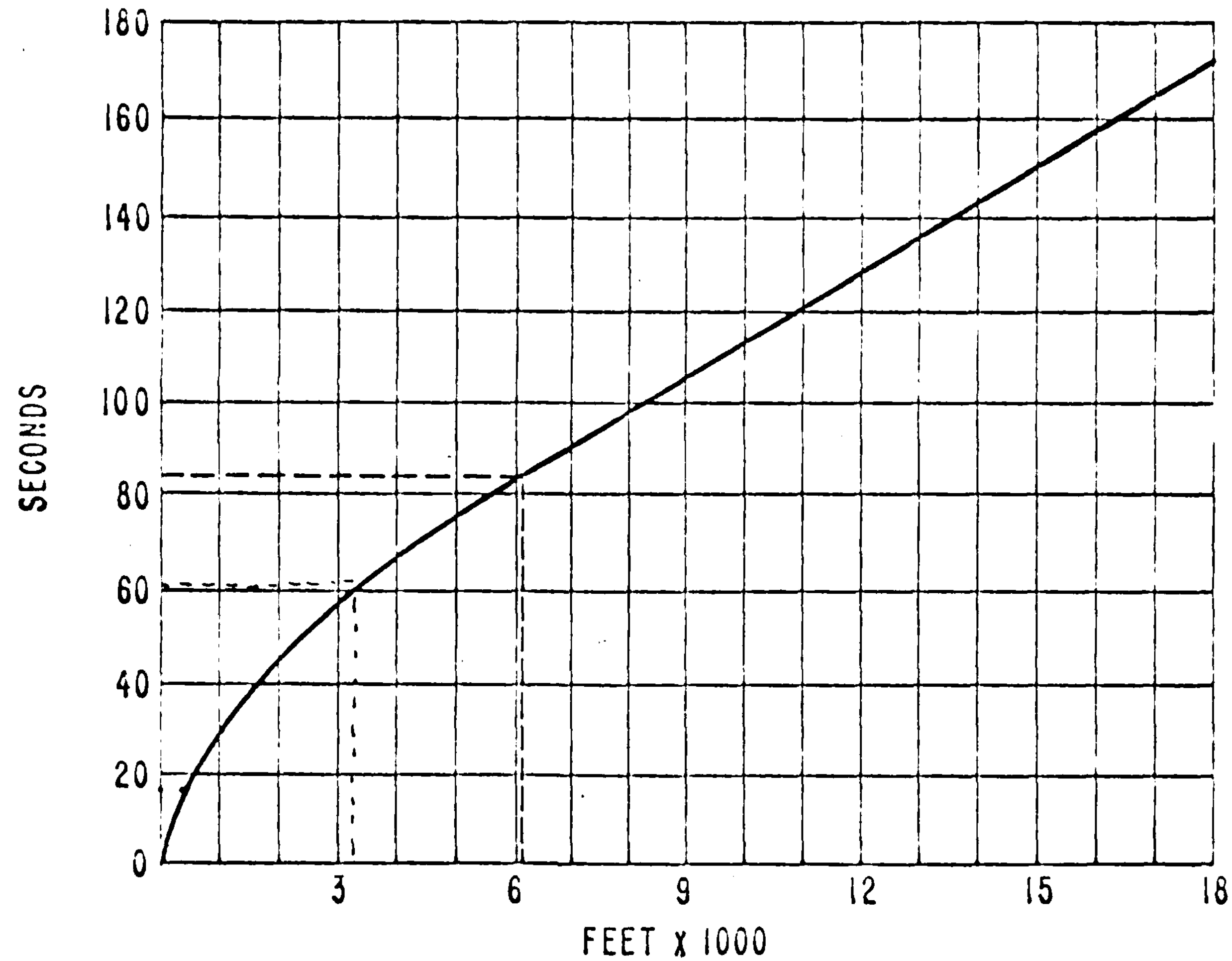


FIG. 1. DISTANCE vs TIME TO TOUCHDOWN DECELERATED APPROACH
80 KNOTS - INITIAL GROUND SPEED

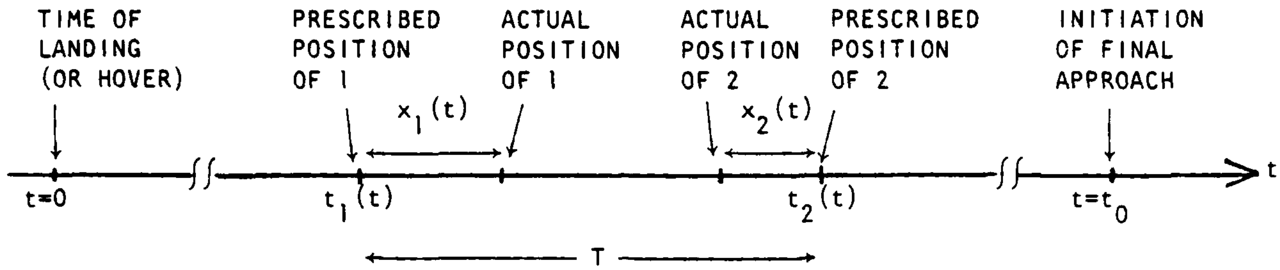


FIG. 2: SCHEMATIC REPRESENTATION OF THE VARIABLES.

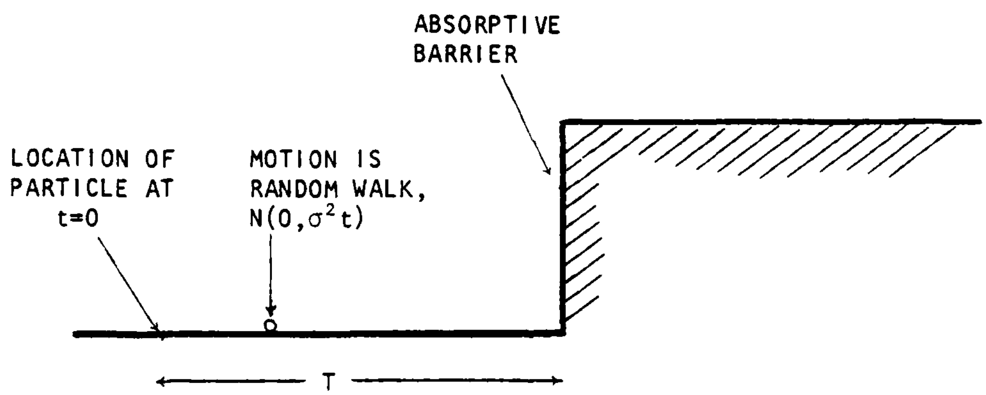


FIG. 3: SCHEMATIC REPRESENTATION OF PHYSICAL ANALOGUE
TO OUR PROBLEM.

Assumption 1: The final approach is executed in an open loop environment, i.e. without benefit of feedback from a ground controller. The two helicopters, in addition, cannot "see" each other (visually or through instruments).

Assumption 2: The deviations $x_1(t)$ and $x_2(t)$ of the two helicopters from their prescribed time positions are independent random variables.

Assumption 3: No lateral deviations from the prescribed one-dimensional path occur, i.e. both helicopters will fly within the same one-dimensional "spaghetti tube" from beginning to end of final approach.

From Assumption 3 it now follows that a collision will occur if at any time t during the interval $[0, t_0]$ the quantity $x_1(t) - x_2(t)$ becomes equal to T. Our problem then can be succinctly stated as: "Find a value of the initial separation T such that*

$$\text{Prob}\left\{x_1(t) - x_2(t) = T \quad \text{for any} \quad t \in [0, t_0]\right\} < p$$

for some given value of p (e.g., $p = 10^{-6}$)".

We shall solve this problem below. At this stage, however, it should be noted that Assumptions 1 - 3 are conservative ones, i.e. on the safe side, and consequently the problem that we shall solve is likely to yield a conservative estimate (i.e. an upper bound) for the required value of T.

Analysis

To answer our problem we must make a specific assumption regarding the probability distribution of random variables $x_1(t)$ and $x_2(t)$. Because of Assumption 1, it is not unreasonable to assume that $x_1(t)$ and $x_2(t)$ are

*Prob {A} denotes the probability of event A.

Gaussian random variables, each with zero mean and with variance equal to $\sigma^2 t$. Physically, this means that on the average each helicopter would be running "neither ahead nor behind schedule" but that there would be a tendency to "drift" away from the prescribed time schedule at a rate of σ time units per unit of time. The longer the helicopter has been flying the final approach path, the more likely it is to have drifted away, as indicated by the linear dependence of the variance ($\sigma^2 t$) on the elapsed time (t).

From Assumption 2 it then follows that if we define a new random variable $X(t) = x_1(t) - x_2(t)$, then $X(t)$ is also Gaussian with mean equal to zero and a standard deviation equal to $\sigma\sqrt{2t}$.

Our problem now becomes equivalent to a classical problem in physics (see Fig. 3): A particle is released at time $t = 0$ from point $X(0) = 0$ and performs a <u>random walk</u> with zero mean and a standard deviation equal to $\sigma\sqrt{2}$ per unit of time. Will it hit, <u>for the first time</u>, before $t = t_0$ a "barrier" which is T units away? Or, equivalently, if the "barrier" is an "absorptive" one, will the particle be absorbed before $t = t_0$? It turns out that under the conditions described above the probability of this event, i.e. the probability of collision for an initial separation T, is given by (see Ref. 1, p. 221):

$$\text{Prob}\left\{X(t) = T \text{ in } [0, t_0]\right\} = 2\int_0^{t_0} \frac{T}{\sigma\sqrt{2\pi}}\, t^{-\frac{3}{2}}\, e^{-\frac{T^2}{2\sigma^2 t}}\, dt \qquad (1)$$

To evaluate (1) it is sufficient to use the transformation $y = T/\sigma\sqrt{t}$ to obtain (after some algebra):

$$\text{Prob}\left\{X(t) = T \text{ in } [0, t_0]\right\} = 2 \int_{\frac{T}{\sigma\sqrt{t_0}}}^{\infty} \frac{e^{-\frac{y^2}{2}}}{\sqrt{2\pi}} \, dy \tag{2}$$

Expression (2) can be written as:

$$\text{Prob}\left\{X(t) = T \text{ in } [0, t_0]\right\} = 1 - 2\phi\left[\frac{T}{\sigma\sqrt{t_0}}\right] \tag{3}$$

where $\phi(z)$ is the well-known (and extensively tabulated) cumulative distribution of the normal random variable, i.e.

$$\phi(z) = \int_0^z \frac{e^{-\frac{y^2}{2}}}{\sqrt{2\pi}} \, dy \tag{4}$$

From (3) we see that, for any desired level of safety (i.e. for any given probability of collision, p, which should not be exceeded) it is possible to determine T from the equation

$$p = 1 - 2\phi\left[\frac{T}{\sigma\sqrt{t_0}}\right] \tag{5}$$

<u>Numerical Application</u>

When the desired p in (5) is very small, as it is likely to be in practical applications, the solution of (5) will involve the extreme tails of the normal distribution for which the value of the function $\phi(z)$ may not be tabulated.

In such cases, it is best to work with a series expansion of (4), i.e. to re-write (5) as:

$$p = e^{-\frac{z^2}{2}} \cdot \sqrt{\frac{2}{\pi}}\,\frac{1}{z}\left(1 - \frac{1}{z^2} + \frac{1\cdot 3}{z^4} - \frac{1\cdot 3\cdot 5}{z^5} + \ldots\right) \tag{6}$$

where $z = \dfrac{T}{\sigma\sqrt{t_0}}$. [The derivation of (6) requires some tedious algebraic manipulation.]

Since z is likely to be considerably greater than 1 [z is the number of standard deviations of the normal distribution that we desire in (5) in order to have a very small probability of collision] we can, as an approximation, ignore all but the first term in (6) and obtain the equation

$$p = \frac{1}{z}\sqrt{\frac{2}{\pi}}\; e^{-\frac{z^2}{2}} \tag{7}$$

Let now $p = 10^{-a}$ where a is an integer. Then, solving (7) by taking natural logarithms on both sides and by setting $u = z^2$, one obtains:

$$-a\,\ell n\ 10 = -\frac{u}{2} + \frac{1}{2}\,\ell n\,\frac{2}{\pi} - \frac{1}{2}\,\ell n\,u$$

or,

$$\ell n\ u = 2a\ \ell n\,10 + \ell n\,\frac{2}{\pi} - u \tag{8}$$

One can then solve (8) for u (which can be done easily with a hand calculator or by using semi-log paper) and then set $\sqrt{u} = T/\sigma\sqrt{t_0}$ in order to determine T.

Numerical Example

(This numerical example is for illustration purposes only and should not be construed as a suggestion of a desirable T since it is based on completely hypothetical numbers with no basis on experience.)

Let us assume that we wish to have a probability of collision p equal to 10^{-6} or less. Then, setting a = 6 in (8) we obtain u = 24, approximately.

For the case shown in Fig. 1, in which it takes about 84 seconds to execute the final approach, let us assume that the standard deviation $\sigma\sqrt{t_0}$ for the whole approach procedure is about 9 seconds (i.e. the standard deviation on the time $t_0 = 84$ seconds is 9 seconds). Then we have $\sqrt{24} = T/9$ or $T = 44.1$ seconds to assure a probability of 10^{-6} or less of a collision. At a velocity of 80 knots (see Fig. 1) this implies a separation of about 6,000 ft (1 n. mile) between helicopters at the beginning of the final decelerated approach. A T of 44.1 seconds also implies a landing rate of about $3{,}600/44.1 = 82$ helicopters per hour.

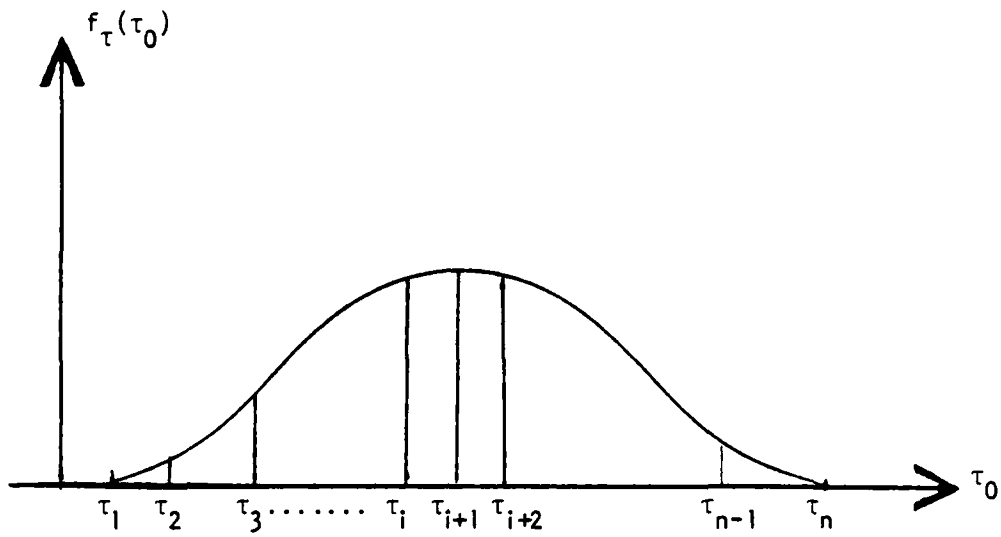
A Model Extension

This model assumes that helicopters at the beginning of the final decelerated approach are spaced exactly T seconds apart and then "drift" from their ideal separation as they approach the intended landing point. The main problem with this model is that it assumes perfect initial spacing between the two helicopters, equal to the desired spacing T. In practice, the actual initial spacing, τ, will be a random variable with some probability density function $f_\tau(\tau_0)$ and with $E[\tau]=T$. That is, while "on the average" τ will be equal to T, sometimes it could be considerably less or more than T.

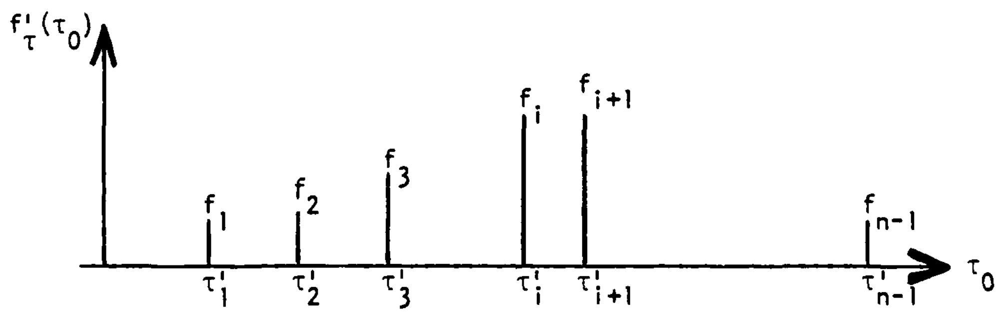
We must, therefore, repeat the analysis for this more realistic situation. While it seems difficult to solve this problem analytically and obtain a

closed-form solution, it is a straightforward matter to solve it numerically for any given $f_\tau(\tau_0)$. We now describe how to do this.

Consider the following probability density function $f_\tau(\tau_0)$:



As seen we have subdivided the range of τ ($\tau_1 \leq \tau \leq \tau_n$) into (n-1) sub-intervals. (In general, it is not necessary that $\tau_{i+1}-\tau_i = \tau_{j+1}-\tau_j$ for $i \neq j$. Also, obviously, the more accuracy we desire of our numerical procedure, the more sub-intervals we use. We now approximate $f_\tau(\tau_0)$ as follows:



In this approximation:

$$\tau_i' = \frac{\tau_{i+1} + \tau_i}{2} \qquad (i = 1,2,\ldots\ldots, n-1)$$

$$f_i = \int_{\tau_i}^{\tau_{i+1}} f_\tau(t)\,dt \qquad (i = 1,2,\ldots\ldots, n-1)$$

After this approximation, the probability of a collision becomes equal to:

$$\text{Prob}\left[\text{collision}\right] = \sum_{i=1}^{n-1} f_i \cdot \text{Prob}\left\{\text{collision}\,\middle|\,\begin{array}{l}\text{initial spacing}\\ \text{is equal to } \tau_i'\end{array}\right\}$$

The quantity $\text{Prob}\left\{\text{collision}\,\middle|\,\begin{array}{l}\text{initial spacing}\\ \text{is equal to } \tau_i'\end{array}\right\}$, i.e. the conditional probability of a collision given that the initial spacing is exactly equal to τ_i', can be evaluated in the manner described above. Thus, in order to evaluate the unconditional probability of collision, we must repeat the procedure outlined above a total of n-1 times. It is simple to write a computer program to do so.

Comment: In all the above discussion, we could have used the "probability of a missed approach" rather than the "probability of a collision" as our measure of safety. In such an event, instead of quantities such as 10^{-6}, 10^{-7} or 10^{-8}, we would be dealing with probabilities of the order of 10^{-2} or 10^{-3}. Otherwise nothing in the above analysis would change.

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2. A. D. Little, Inc., "A Study of Air Traffic Control System Capacity," Federal Aviation Administration Report No. FAA-RD-70-70, October 1970.

3. Masters, C. O., "Preliminary Investigation of Separation Criteria for Closely Spaced IMC Helicopter Traffic, Performing Decelerated Instrument Approaches," paper presented at Aviation Electronics Symposium of the Army Aviation Association of America, Fort Monmouth, New Jersey, March 1979.

APPENDIX 3

THE KINEMATICS OF THE INTERCEPT VECTOR

The kinematics of determining a vector to cause an intercept of a moving box and a constant velocity target can be expressed very simply as a function of the relative speeds, and the relative positions. We ignore turning radii and times to turn for the present.

Consider Figure 1. At time $t = 0$ the box is at the origin moving along the x axis at a range rate $\dot{r}$. The target is at a point (x_0, y_0) and has a constant ground speed V. The intercept problems can be stated as:

1. Is it possible to intercept the box?
2. What heading θ is required to intercept?
3. What is the time to intercept?

The equations of motion are:

$$r = \dot{r} \quad t$$

$$\dot{x} = V\cos\theta \qquad x = x_0 + V\cos\theta \cdot t$$

$$\dot{y} = V\sin\theta \qquad y = y_0 - V\sin\theta \cdot t$$

At intercept, $y = 0$, and $x = r = \dot{r} \cdot t$

Thus,

$$y_0 = V\sin\theta \cdot t \tag{1}$$

$$\dot{r} \cdot t = x_0 + V\cos\theta \cdot t \tag{2}$$

From (1), the time of intercept, $t_i = \dfrac{y_0}{V\sin\theta}$

From (2), substituting for t

$$\frac{\dot{r} - V\cos\theta}{V\sin\theta} = \frac{x_0}{y_0} \tag{3}$$

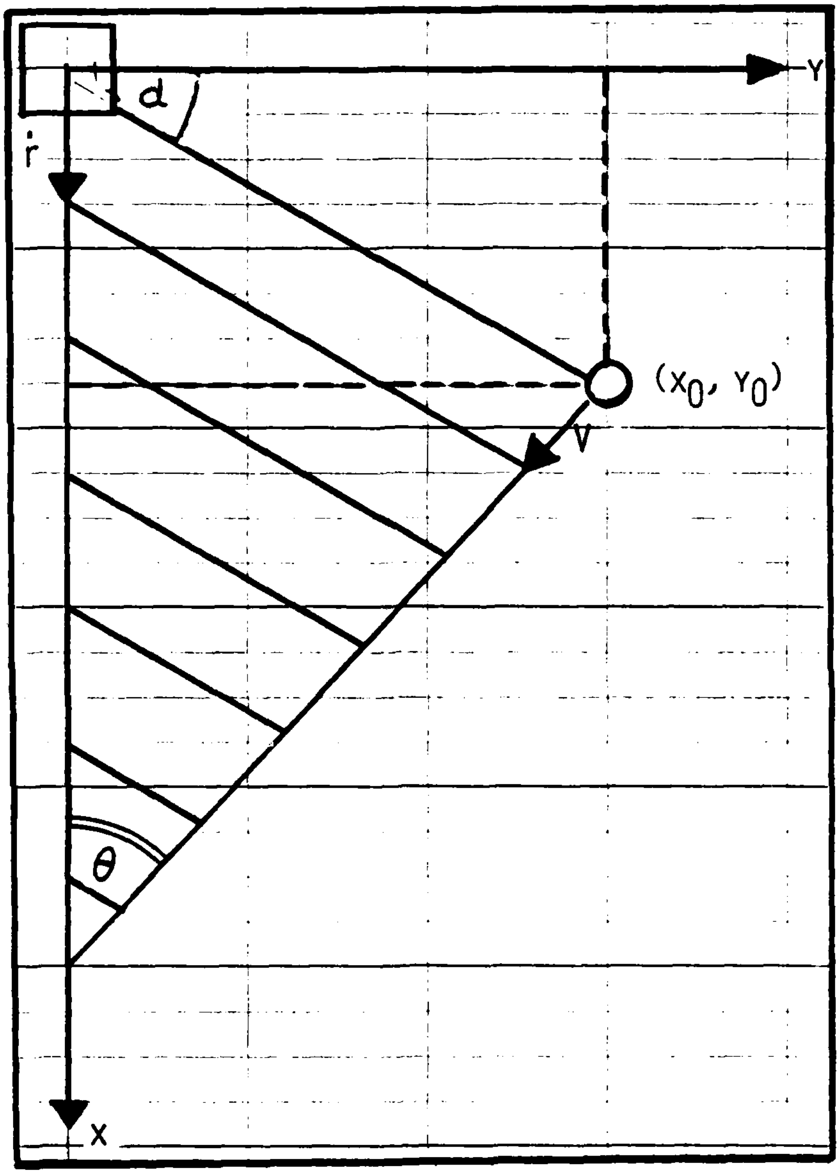

FIG. 1: THE INTERCEPT GEOMETRY

or

$$\frac{\dot{r}}{V} = \cos\theta + \left(\frac{x_0}{y_0}\right)\cdot\sin\theta \tag{3a}$$

From (3), if we know the ground speed ratio $\frac{\dot{r}}{V}$, and the relative position $\frac{x_0}{y_0}$, we can solve for the intercept angle θ.

The geometry is shown in Fig. 3.1. The parallel lines indicate successive time positions at intervals Δt of the box and target before intercept. If we denote

$$\alpha = \tan^{-1}\left(\frac{x_0}{y_0}\right)$$

as the relative bearing of the target from the box, then we can state the following:

a) If $V < \dot{r} \cdot \cos\alpha$, then no intercept is possible. This can be seen in Fig. 3.1, by showing that no vector $V \cdot \Delta t$ can be found which will cut the first parallel line.

b) At $V = \dot{r} \cdot \cos\alpha$, the intercept angle $\theta = \alpha$, and the target is moving perpendicular to the parallel lines.

c) At $V > \dot{r} \cdot \cos\alpha$, there are intercept points with $\theta > \alpha$. For $V = \dot{r} \cdot \cot\alpha$, $\theta = 90°$. For $V = \dot{r}$, $\theta = 2\alpha$, and the intercept triangle is isosceles.

Since we have proposed the case where $V = \dot{r}$, then we know that the final intercept heading θ will be 2α. This explains the display format where a "Wand" of 15° is used to determine the time to call the final vector of 30°. With similar logic, it is possible to guide the aircraft onto a 90° vector such that it is late for 90° intercept and will be called to the final vector within the ±30° final vectoring area. These times for commands can be

Indicated on the display by having the target flash, and display the heading. Both the 90° and 30° vectors are selectable, or can be varied in the logic for automatically generating final vectoring commands.

The Dynamics of Vectoring

The above analysis is static. In the real case, there will be errors due to time lags in communication and response, errors due to surveillance data, and errors due to uncertain wind speeds. The logic can be extended to account for the periods of time spent in changing headings. At a standard turn rate of 3°/second it is not negligible, and the impact of turning radii will lead to early calls for heading changes.

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